

APPENDIX B: NASA Analysis*

*[Editor's note: Because of space considerations, certain photographs and the test procedure (appendix A to the NASA report) are not included here. Interested parties may request a full copy of the report, including these omitted materials, by contacting the CSB at the address indicated in the Abstract. References to the "one inch pipe" in this appendix correspond to references to the ¾-inch schedule 80 outlet pipe to the vaporizers in the body of the CSB report. References to excess flow valves A14 and A33 in the NASA report do not correspond precisely to items A14 and A33 listed in Appendix C.]

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KSC-MSL-0741-1998

SUBJECT: Analysis of the Excess Flow Control Valves and Metallurgical Studies of a Propane Storage Tank Involved in the Boiling Liquid Expanding Vapor Explosion (BLEVE) near Albert City, Iowa.

RELATED DOCUMENTATION: KSC-MSL-0741-1998-03
KSC-MSL-0741-1998-01
REGO Catalog L-500, ECII, Section F
Manufacturer's Data Report For Unfired Pressure Vessels,
Form U-1-A, National Board Number 5446

1.0 ABSTRACT

The four excess flow control valves from the subject propane tank were tested using water at various pressures and flow rates and found to behave as they were designed to function. The material composition of the propane tank sheet metal was determined to be AISI 1525 (UNS G15250) carbon steel. Examination of the fracture surface of the pipe that connected to the propane vaporizing system indicated that the pipe failed due to an overload (overstress) condition. Metallurgical analyses indicated that the propane storage tank failed via overload (overstress), with no evidence of a pre-existing crack discernible. A portion of the tank appeared to have been heated and deformed, indicating a fire was existing immediately before the event.

2.0 FOREWORD

- 2.1 The Kennedy Space Center (KSC) Materials Science Division (MSD) was contacted by personnel at Oak Ridge National Laboratory, Tennessee, to enlist support in the subject investigation for the U.S. Chemical Safety and Hazard Investigation Board, Washington, D. C. The scope of support was to determine the metallurgical properties of the subject propane tank; the pipe that carried liquid propane to a vaporizer system; and to develop information relevant to the fluid flow components involved in the fire and explosion of the subject propane storage tank.
- 2.2 The explosion occurred on a farm that raised turkeys for market. The propane storage tank contained liquid and gaseous propane used as an energy source to heat the turkey barns in colder weather conditions. It was reported that the pipe beneath the propane storage tank was hit by an all-terrain vehicle and broken open. A fire ensued, and when the storage tank ruptured, two volunteer firemen were victims of the flying debris.
- 2.3 The tank components were collected by Hall Engineering Services, P. C., Ames, Iowa, at the site after the explosion near Albert City, Iowa, and moved to Des Moines, Iowa, for storage and preservation. MSD personnel visited the storage site to determine which items would be sent to KSC for testing; the Albert City site was also visited in an effort to understand events relating to the incident. While in the Albert City area, another farm site was visited that had a similar propane heating system and components.
- 2.4 Two liquid excess flow control valves from the base of the ruptured propane tank were sent to KSC for testing and examination. The two valves are shown installed in the tank section in Figures 1 and 2. Figure 3 shows the excess flow control valve designated FV4 (that previously connected to the liquid tank fill stub) after the valve had been removed from the tank section. Valve FV4 is shown as-received in the laboratory in Figure 4. Figure 5 shows the second excess flow control valve, FV3, as-received in the laboratory. Valve FV3 fed the pipeline connected to the vaporizer system.
- 2.5 The man-way cover containing the two smaller excess control valves is shown in Figure 6. These two excess control valves were used in the vapor side of the propane system. Valve A14, used in the vapor return line for the tank filling system, is shown in Figure 7 as it was received in the laboratory. The excess flow control valve that connected to the vaporizer system, A33, is shown in Figure 8 as it was received in the laboratory. It can be noted in Figure 6 that the three pressure relief valves on the small castle on the man-way have disintegrated and the internal parts have blown out.

- 2.6 The hand valve connected to excess flow control valve FV4 is shown in Figure 9 as it was received in the laboratory. This hand valve was labeled A19. The hand valve that was connected to the flow control valve FV3 is shown in Figure 10, both at the storage warehouse in Des Moines, Iowa, and as-received in the laboratory. The hand valve A20 connected the excess flow control valve to the smaller pipeline that fed the vaporizing unit. (This is the pipe that was reported to have been broken open and been a possible contributor to the incident.) Figure 11 shows this pipe, labeled A1, as-received in the laboratory.
- 2.7 The four flow control valves FV3, FV4, A14 and A33 were manufactured by Engineered Controls International, Inc., 100 Rego Drive, Elon College, North Carolina, 27244. Flow control valves FV3 and FV4, having a three inch inlet connection, are thought to be Part Number A7539T6. Identifying marks were partially obscured or destroyed. Flow control valves A14 and A33 used in the vapor portion of the propane system had a two inch connection, and are thought to be Part Number A7537L4 for similar reasons. Hand valves A19 and A20 were manufactured by Fisher, with “400WOG” and “Ductile” cast into the valve body. It is thought that the hand valves may have been manufactured by Fisher Controls, Marshalltown, Iowa, 50158. Hand valve A19 was not used in the testing at KSC.
- 2.8 The three pressure relief valves remaining in the man-way cover were only valve bodies. The internal components are thought to have been expelled prior to the propane tank explosion, probably due to excessive pressures inside the tank. These valves were not removed or tested, as they are not functional in their current condition. It was reported that the pressure relief valves were set to open at 250 psi pressure.
- 2.9 The U-1-A form indicated that the tank was constructed in 1964 in Memphis, Tennessee.

3.0 INVESTIGATIVE PROCEDURES AND RESULTS

- 3.1 MSD personnel performed an on-site examination of the remnants at the storage warehouse in Des Moines, Iowa. Four major remnants of the tank (Figures 12-15) and the pipe (Figure 16 [subject A1]) that connected the vaporizer unit to the valve FV3 were examined visually and with low-power magnification. The fracture surfaces of the head and shell sections of the propane tank were oriented at 45°. One section of the tank shell (Figure 13) appeared to have been exposed to heat and internal pressure, causing necking of the tank material (Figure 17). The exterior of the tank appeared to have been scorched by fire, although the most severe heat damage was concentrated in the necked region of the shell. A section of the tank from the necked region (Figure 17), as well as a section of the tank shell that did not appear to have been affected by the heat (Figure 18), were permitted to be removed. The thinning that occurred on one of the tank sections is shown in

Figure 20. Three sections of steel, approximately one foot square, were cut from the remainder of the tank for metallurgical studies. The cutting operation is shown in Figure 21. Figures 22-24 show the three steel tank specimens. One section of the tank head, adjacent to the welded region near the man-way access port, displayed a lamellar fracture; a section was removed from that region (Figure 25). Destructive testing was authorized on all of the sections removed from the tank. Destructive testing was not permitted on the vaporizer pipe (A1) or other flow components.

- 3.2 The section of the tank shell that exhibited necking (Figure 26), the section that appeared unaffected by the heat (Figure 27), the tank head section (Figure 28), and the vaporizer pipe (Figure 29) underwent stereo- and macroscopic examination at KSC. The fracture surface in the necked-down region appeared corroded and smeared (Figure 30). Likewise, the section that was unaffected by the heat appeared corroded (Figure 31) and severely smeared (Figure 32). A comparison of the necked region with the unaffected region revealed the substantial ductility of the area that had been affected by the heat, i.e., the necked region (Figure 33). The lamellar region (Figures 34 and 35) appeared slightly corroded with minimal post-fracture damage. The end of the vaporizer pipe (Figure 36) that mated with the hand valve (A20) appeared rough and slightly corroded (Figure 37). The end of the pipe was bent approximately 25° with respect to the longitudinal axis. The threads of the pipe displayed mechanical damage (Figure 38), with the threads on the concave side of the bend appearing compressed (Figure 39).
- 3.3 The fracture surfaces of the various sections from the shell and head of the tank were cleaned in a dilute citric acid solution and analyzed via scanning electron microscope (SEM). The fracture surfaces from the necked region of the tank shell (Figure 40) displayed microvoid coalescence (MVC), typical of ductile overload. Likewise, the fracture surface from the tank head displayed MVC (Figure 41). A laboratory-induced overload exemplar of the shell displayed MVC (Figure 42).
- 3.4 Inductively coupled argon plasma and combustion spectrometric methods revealed that the specimens from the head and shell of the tank had compositions similar to a high-strength manganese-bearing carbon steel, similar to UNS G15250.
- 3.5 Sections of the head and shell were prepared for metallographic examination. The necked section (Figure 43) of the tank shell displayed extensive deformation of the pearlitic grains (Figures 44 and 45). The microstructure of the shell that appeared unaffected by the heat consisted of pearlite in a ferritic matrix (Figures 46 and 47). The microstructure of the tank head section that displayed lamellar features consisted of a banded pearlitic microstructure (Figure 48). Converted microhardness measurements of the necked shell section averaged 90 Rockwell B (HRB) scale, corresponding to an approximate

tensile strength of 89 ksi. Converted microhardness measurements of the unaffected area averaged 87 HRB scale, corresponding to an approximate tensile strength of 84 ksi. Converted microhardness measurements of the head section from the tank averaged 24 Rockwell C scale away from the lamellar region, corresponding to an approximate tensile strength of 118 ksi. Measurements adjacent to the lamellar region averaged 90 HRB, corresponding to an approximate tensile strength of 89 ksi.

- 3.6 The components described above in Figures 1-11 were transported from the storage site warehouse in Des Moines, Iowa, to Hall Engineering Services, P.C., Ames, Iowa, for packaging and then transported to KSC. After testing was completed, the components along with the tank material were returned to Hall Engineering Services, Ames, Iowa.
- 3.7 The test setup is shown in Figure 49. Figure 50 shows the hardware setup and Figure 51 shows a close-up of the tank base housing the excess flow control valve and the horizontal discharge pipe. Figure 52 shows a typical test run. Water was discharged from the pressurized holding tank, through the test items onto a paved area and into a storm drain at the Launch Equipment Test Facility (LETF) at KSC. A three inch ball valve was used in the pipe setup to facilitate rapidly opening the flow path.
- 3.8 The test procedure and recorded results are contained in Appendix A. Twenty-eight (28) different test runs were conducted to generate data that simulated various physical conditions and combinations of equipment. The tests verified that the excess flow control valves operated at certain conditions and did not operate at other flow conditions.

4.0 DISCUSSION

- 4.1 The failure of the tank likely originated at the necked region of the shell where it had been heated. The pressure in the tank increased until the weakened section burst. The remainder of the tank displayed typical overload features, both optically and fractographically. No evidence of a pre-existing crack was observed. The corrosion on the various fracture surfaces was post-fracture and not considered a contributing factor.
- 4.2 The vaporizer pipe appeared to have been broken mechanically from the reducer bushing in hand valve A20. Due to the constraint of not being able to dissect the pipe in the laboratory, further analysis was not possible. The corrosion on the fracture of the pipe was post-fracture and not a contributing factor.
- 4.3 The head and shell sections of the tank had compositions corresponding to a high strength carbon steel. Converted microhardness measurements corresponded to tensile strengths above the minimum 70 - 75 ksi typically used

for similar components. The lamellar and banded structure observed on the propane tank head section sample corresponded to the heat affected zone of a weld adjacent to the man-way access.

- 4.4 The excess flow control valves were individually tested using water and various pressures. The water flow rates were also measured and recorded. The valves closed when the ball valve in the experimental set-up was opened and water allowed to flow through the three inch discharge pipe.
- 4.5 When flow control valve FV3 and hand valve A20 were tested in series, the liquid flow was restricted due to the reducer bushings installed in the hand valve outlet to accommodate the one inch pipe leading to the vaporizer units. The reduced flow was insufficient to cause the excess flow control valve to close, resulting in the continuous flow seen in Figure 20. This test condition comes closest to simulating the flow conditions that likely existed at the time the propane storage tank exploded.

5.0 CONCLUSIONS

- 5.1 The one inch pipe that fed the vaporizer units failed from mechanical overload.
- 5.2 The excess flow control valve in the flow path feeding liquid propane to the vaporizer units did not close during the tests simulating conditions thought to exist at the time of the explosion because the flow of water was restricted by the reducer bushings installed in the outlet of the hand valve downstream of the flow control valve.
- 5.3 The shell of the propane storage tank necked down prior to fracture. The necking was facilitated by heat from the fire and high pressure inside the tank. The fracture in the steel of the tank shell was due to overload. The material was AISI 1525 (UNS G15250) carbon steel that failed in maximum shear stress. No evidence of any pre-existing crack in the tank shell material was observed.

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FIGURE 1

The two liquid excess flow control valves in the tank section prior to removal for testing purposes.

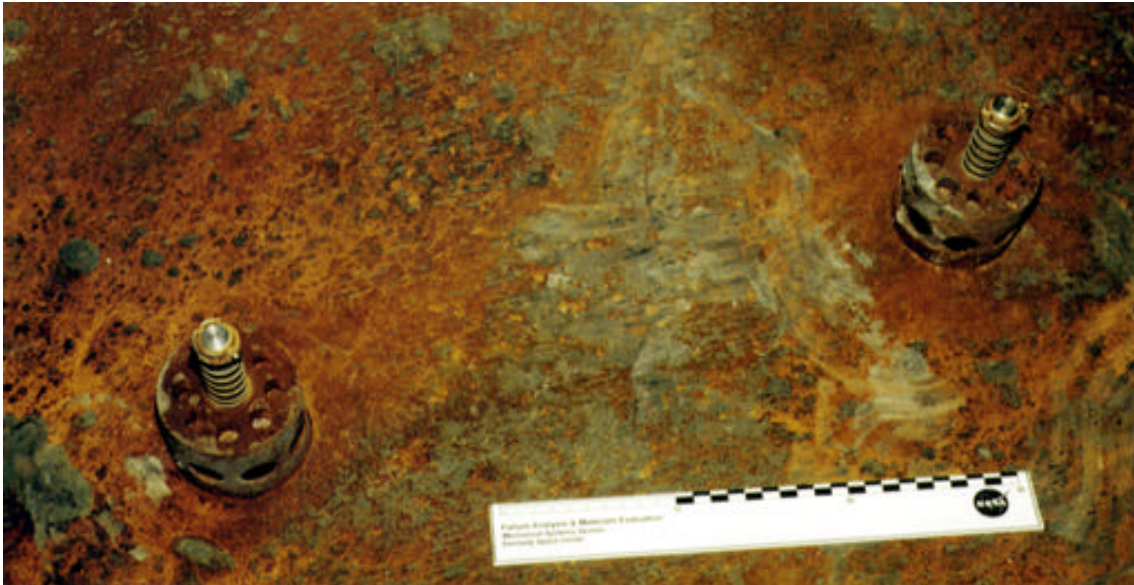


FIGURE 2

The two liquid excess flow control valves as seen from the interior side of the tank section.



FIGURE 5

Liquid flow control valve FV3 as-received in the laboratory.



FIGURE 6

Propane tank man-way cover as seen in the Des Moines, Iowa storage warehouse. Vapor excess flow control valves are labeled A14 and A33. Three pressure relief body shells can be seen on the elevated connection plate.

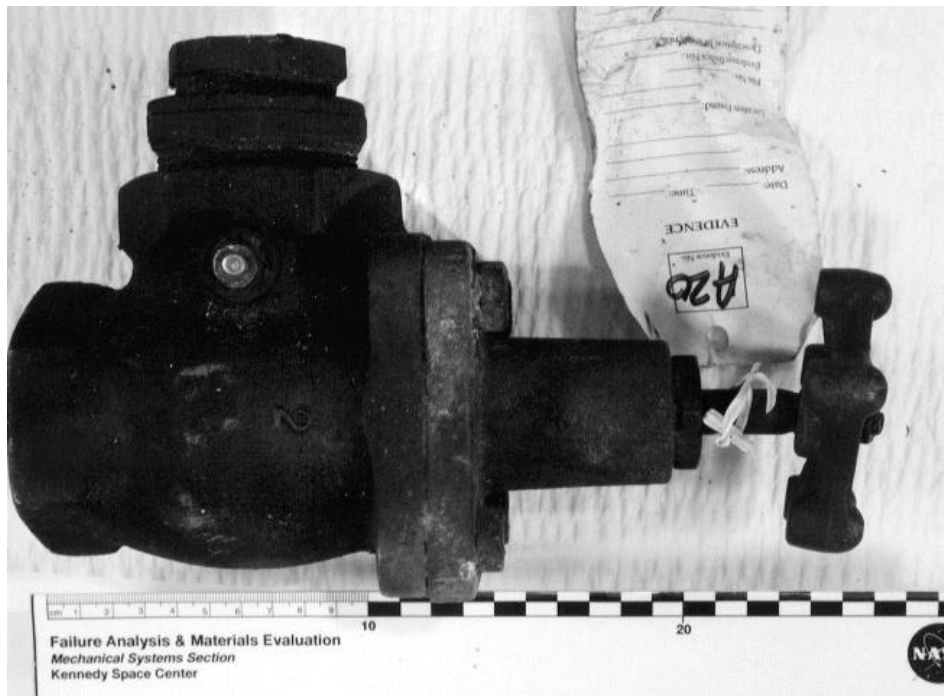


FIGURE 10

The lower view is the hand valve A20 as-received in the laboratory.



FIGURE 11

Fracture surface of the one inch pipe that previously connected to hand valve A20.



FIGURE 29

View of the pipe that fed liquid propane to the vaporizer units.



Figure 37
View of the fracture surface of the one inch pipe (A1) which carried liquid propane to the vaporizer unit

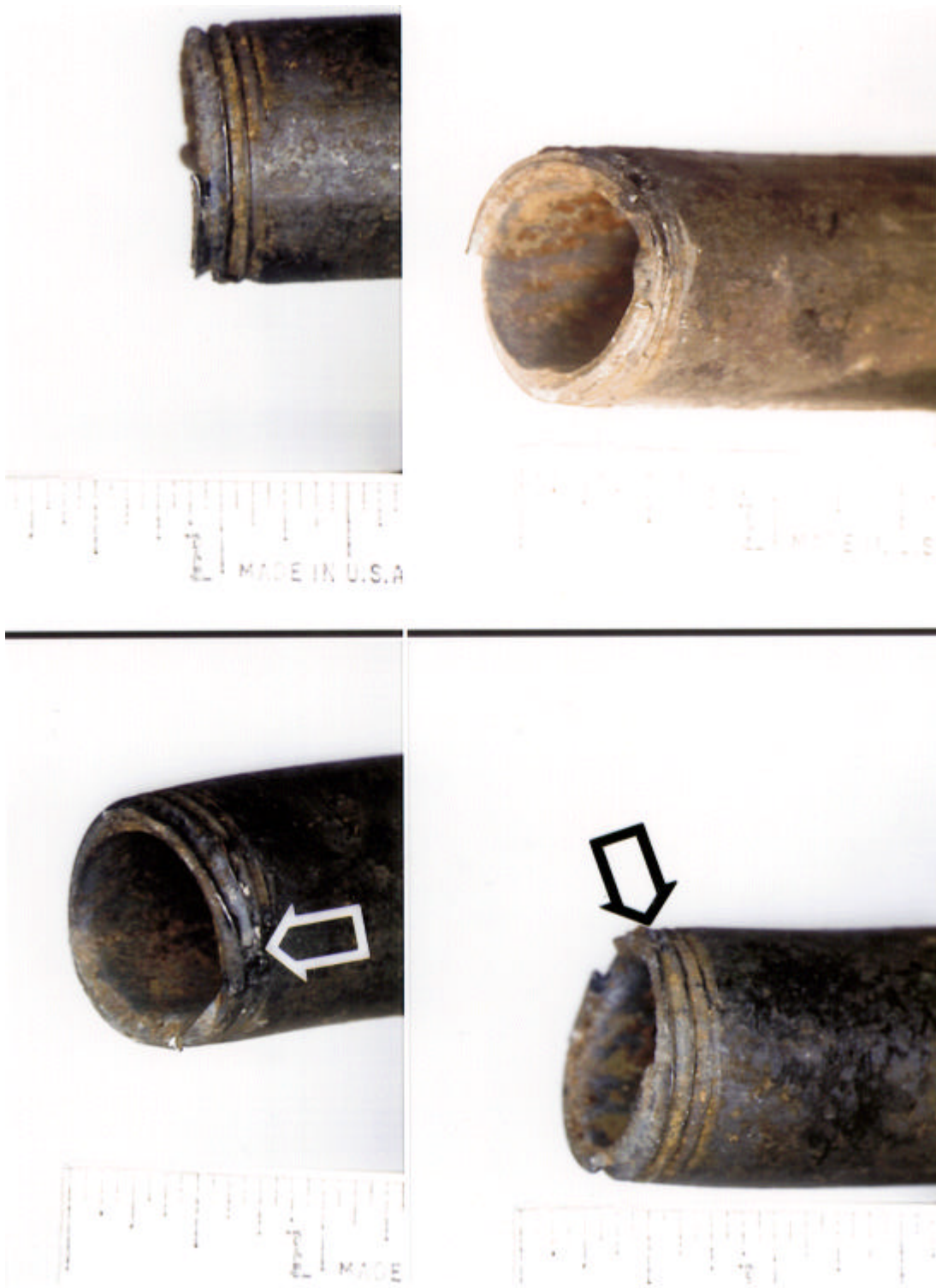


Figure 38

90° rotational view of the threaded end of the one inch pipe (A1). Arrow indicate deformed threads.



Figure 39
90° rotational view of the condition of the pipe threads on the one inch pipe (A1).
MAGNIFICATION: 5X